Hunting Waves in Space

Gravitational Wave Research with dSPACE Equipment

The Crab Nebula in the constellation of Taurus is the detritus from a supernova that occurred approx. 900 years ago and is a typical source of gravitational waves.

Detecting gravitational waves is one of the unsolved challenges in physics. Albert Einstein predicted their existence in 1915, but he doubted it would ever be possible to detect them. Now modern observation technology has brought this within reach. With the help of dSPACE equipment, researchers at the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the USA have set up an observatory dedicated to detecting gravitational waves.

If all goes as planned, LIGO, the laser interferometer, will detect gravitational waves for the very first time (seen here is the installation in Hanford, Washington). Each of the interferometer's two arms is 4 km long. Pictures courtesy of the LIGO Project

Ripples in Space

Any suitably asymmetric system of accelerated masses generates gravitational waves. These propagate at the speed of light and briefly deform space and all the objects in it as they pass through. These deformations are minute, however. Even if a star in our galaxy exploded – a supernova – the resulting gravitational wave would distort the 150-million-kilometer distance between the Sun and the Earth by just the diameter of a hydrogen atom. And for only a thousandth of a second. The idea that a gravitational wave could shake us like an earthquake is pure science fiction. That's what makes detecting them so incredibly difficult. But despite the fact that they are so weak, gravitational waves would provide valuable information on the Universe – which is why researchers are so interested in them.

> "The dSPACE equipment met our requirements and enabled us to complete the work successfully in the time and budget we had allocated."
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> *Dr. Mark Barton, California Institute of Technology*

How to Detect Gravitational Waves

Because gravitational waves briefly deform everything in their path, there is one obvious method of detecting them: Monitor the length of a defined distance very accurately. If you observe a sudden variation in length, this might be because a gravitational wave just passed through. The distance needs to be as long as possible, because the longer it is, the more it is deformed. We made this idea for a gravitational-wave observatory a reality by using a laser interferometer. Laser interferometers exploit the wave properties of light to measure lengths precisely and already proved useful as optical "precision rulers" in numerous fields.

Unlike a classic observatory, a gravitational-wave observatory does not need a clear view of a starry sky, since gravitational waves can penetrate any material, even the Earth, without obstacle. So it makes no difference where the observatory is located and which way it is facing – giving it an obvious advantage over conventional observatories.

LIGO: The Gravitational-Wave Observatory

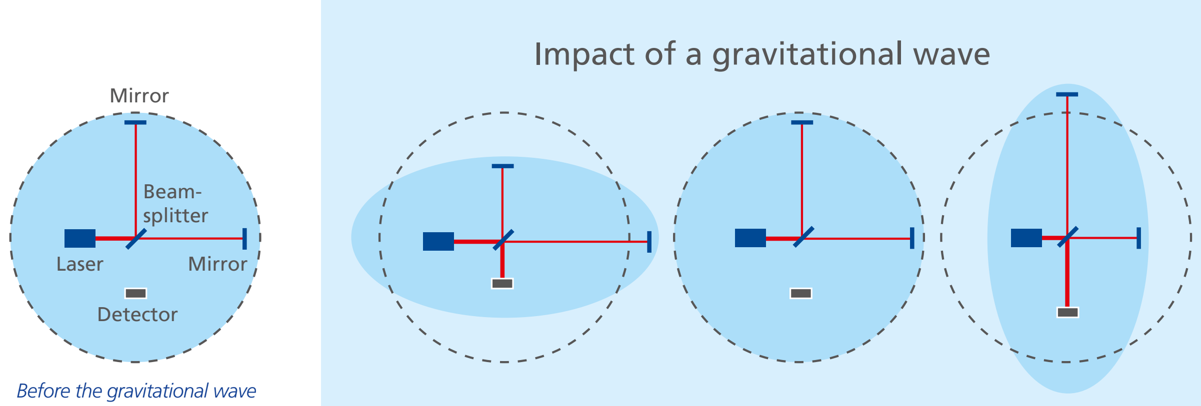
In LIGO (Laser Interferometer Gravitational Wave Observatory), a semi-transparent mirror splits a laser beam. The two half-beams then run along two 4-km beam tubes at right angles to each other. Because each half-beam makes about 50 roundtrips between a pair of mirrors in the interferometer arm, the 4-km arm has the same sensitivity as if it were 200 km long. The half-beams are finally recombined in a photodetector in such a way that they cancel each other out precisely (destructive interference), i.e., the

image on the photodetector remains dark. When a gravitational wave arrives, the lengths of the two arms are deformed in opposite senses, so the half-beams get out of sync and do not cancel each other out completely: a signal appears in the photodetector.
To detect gravitational waves, LIGO has to be able to measure changes in the length of the 4-km interferometer arm that are only a billionth of the diameter of an atom. LIGO is so sensitive that it also registers numerous other effects as disruptive vibrations, for example, sea waves on the coast several kilometers away or a tractor working in a distant field. The main challenge is therefore to isolate the entire facility from this background noise. Because it is the distances between the pairs of arm mirrors that are sensitive to the gravity wave, the suspensions for these "test mass" optics require particular care in design. We implemented active damping for them with the aid of a dSPACE prototyping system.

dSPACE Equipment Stops Seismic Noise

All of LIGO's main mirrors are suspended from thin wires as a series of pendulums. This alone reduces vibrations above the pendulums' eigenfrequencies without any further intervention. In Initial LIGO, all the hanging masses were supported by simple single-stage wire loops, but for the forthcoming Advanced LIGO upgrade, we are planning a much more ambitious set of suspensions. The most elaborate of these will be a pair of quadruple pendulums, each with one glass and two metal auxiliary masses. To prove that we could model, control and damp such a complicated system we instrumented the prototype with 20 sensors and actuators distributed around the suspension system to absorb any shocks as fast as

Schematic of the effects of being hit by a gravitational wave (greatly exaggerated for clarity).



Before the gravitational wave passes through, both arms of the interferometer have equal length, the image in the detector remains dark (destructive interference)

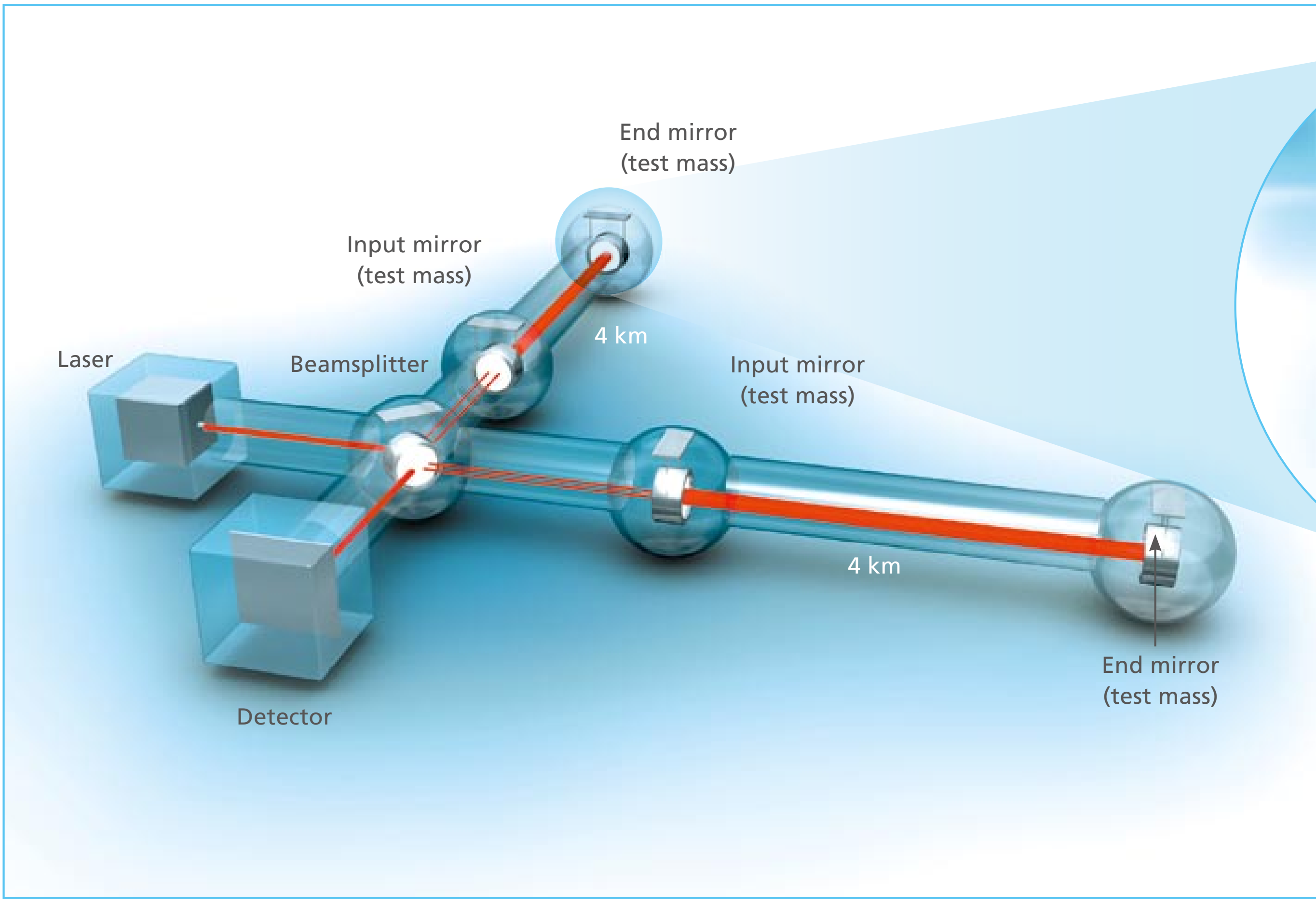
When the gravitational wave passes through, it distorts the arms of the interferometer in an alternating fashion. The detector senses the difference in length as an oscillating signal.

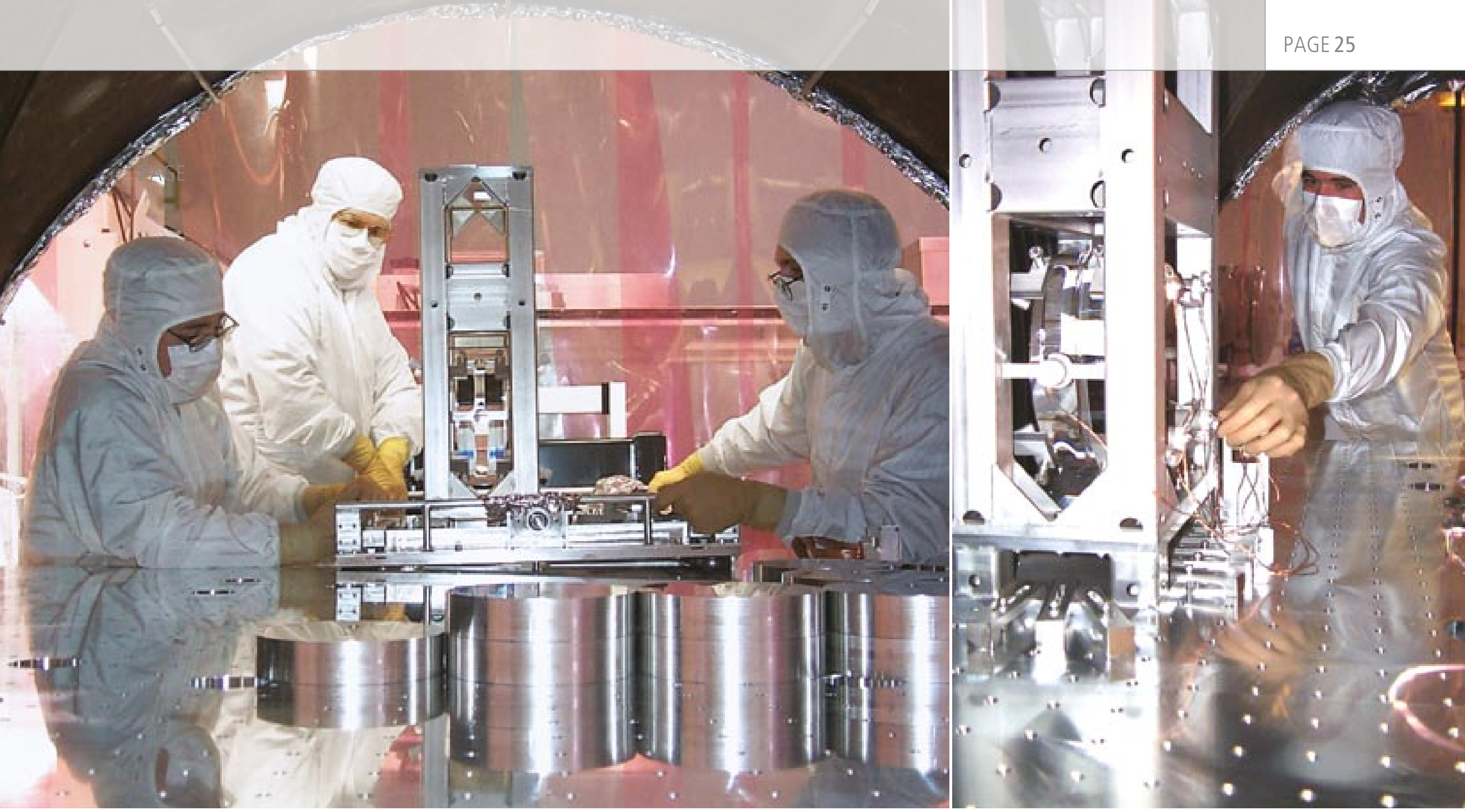
possible. Each sensor is a combination of an LED and a photodiode that registers mirror deflection when the light beam between the two is interrupted by a flag. The actuators consist of voice coils that use the sensor signals to keep the mirrors motionless by acting on magnets. The sensor signals are registered via a dSPACE DS2003 Multi-Channel A/D Board, after which a dSPACE DS1005 PPC Board calculates the appropriate output values, which it transmits to the actuators via several DS2102 High-Resolution D/A Boards. We developed the model for the control with MATLAB®/Simulink®, and the entire experiment is monitored via dSPACE ControlDesk. This easy-to-use combination of MATLAB/Simulink with dSPACE hardware and software enabled us to concentrate completely on the actual experiment and easily stay on schedule. Several test runs with artificially generated disturbance signals verified that the control system was performing correctly.

A Second Observatory – Just to Make Sure

LIGO consists of two identical observatories in different locations in the USA (Hanford, Washington and Livingston, Louisiana). Two observatories are needed to ensure that a presumed gravitational wave is not actually just a local vibration. A real gravitational wave would cause the same signal at both locations, but a local vibration would only occur in one of the installations. Even so, if a presumed gravitational wave signal occurred, it would always be compared with other observatories as well (including ones in Europe and Japan). If the same signal were measured everywhere, that would constitute proof that a gravitational wave had occurred.

Simplified layout of the LIGO gravitational-wave observatory. In the forthcoming Advanced LIGO upgrade, the end mirror suspension will be a quadruple pendulum with a mix of glass and metal upper masses plus a reaction chain of similar design to serve as a quiet reference for applying control forces. The dSPACE equipment made it possible to smoothly design and implement a control system for the prototype. Diagram of suspension courtesy of the University of Glasgow.





Adjusting the mirrors in the LIGO. Picture courtesy of the LIGO Project.

A New Window on the Universe

Up to now, astronomers have used light and radio telescopes to observe the Universe. Gravitational-wave astronomy with LIGO has given them a new window on the Universe. Large parts of the Universe are concealed behind dark clouds that are impenetrable to waves in the visible and radio ranges. Gravitational waves, on the other hand, can penetrate these clouds unhindered to bring us fresh information on unknown areas of the Universe. Moreover, gravitational-wave astronomy will supply additional information to light and radio wave astronomy, and will provide answers to many open questions concerning black holes, neutron stars, colliding galaxies and other phenomena.

Dr. Mark Barton
LIGO Project
Caltech
USA

A combination of dSPACE hardware and software is used to actively dampen the mirrors.